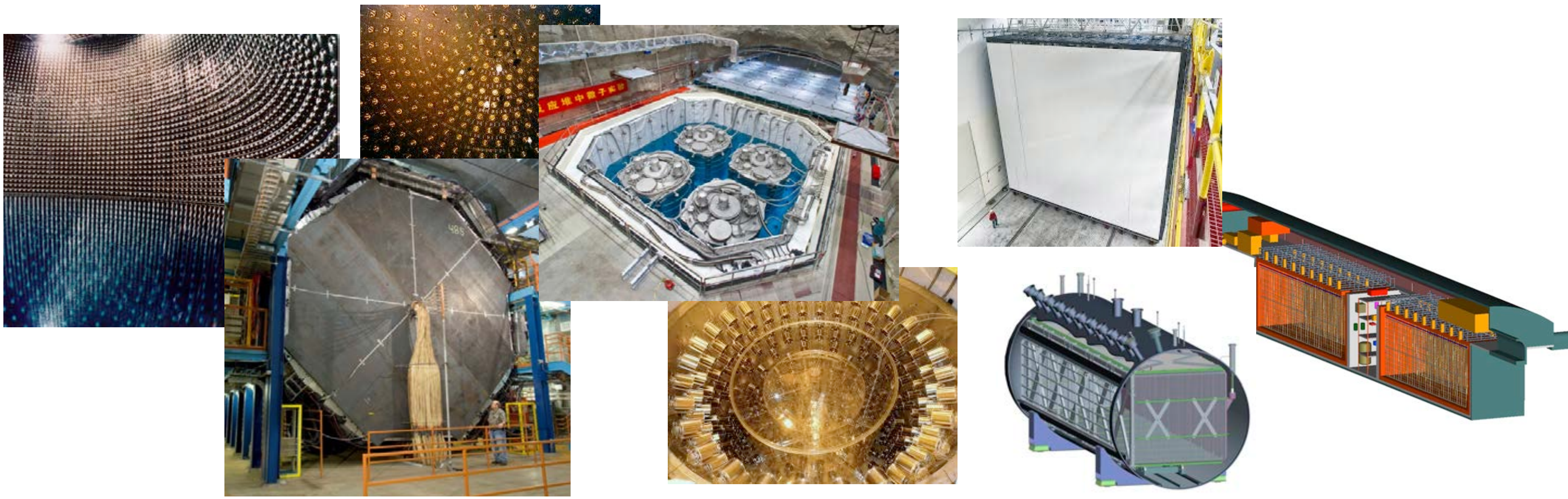
A Discovery Program of Neutrino Experiments

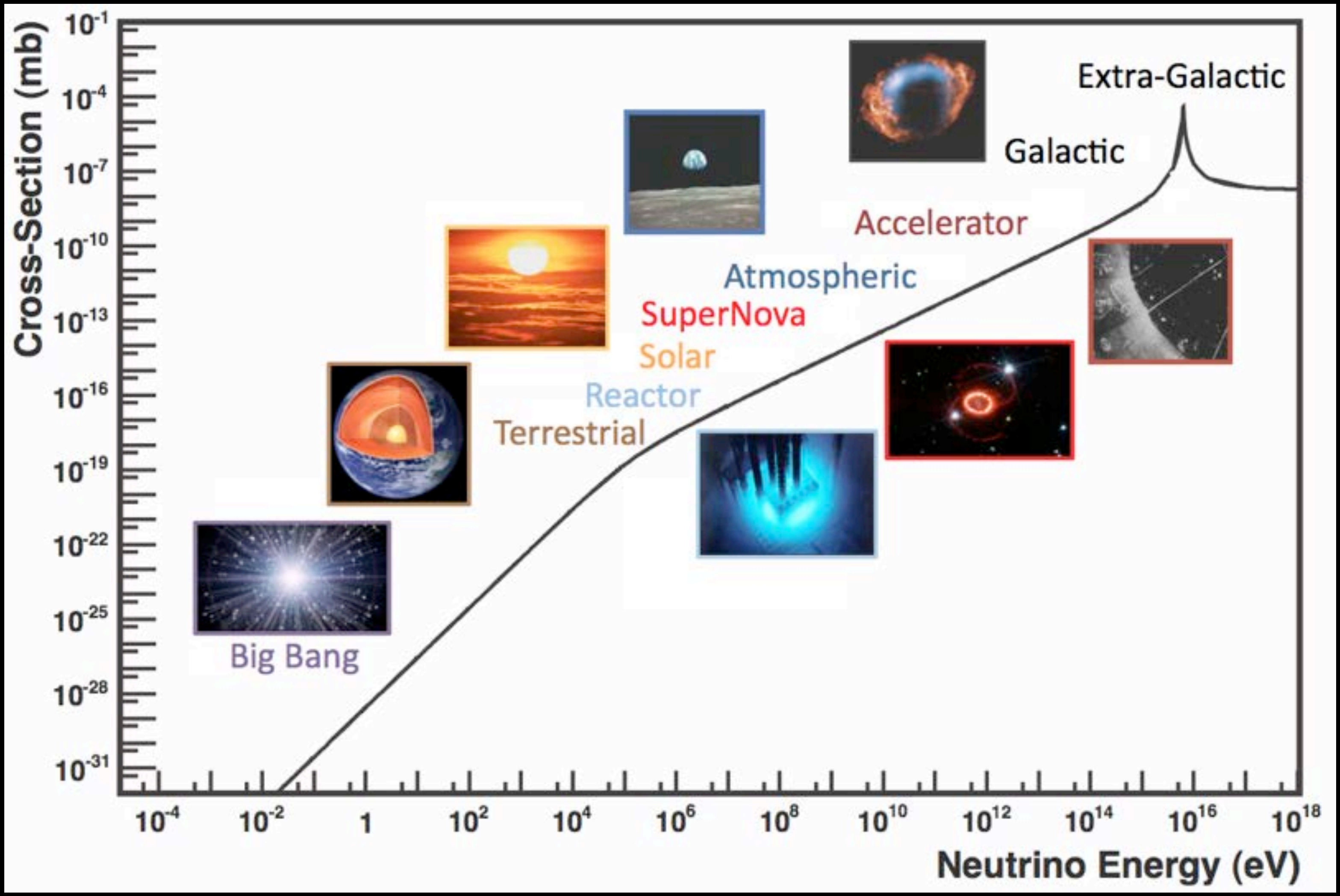


Karsten M. Heeger

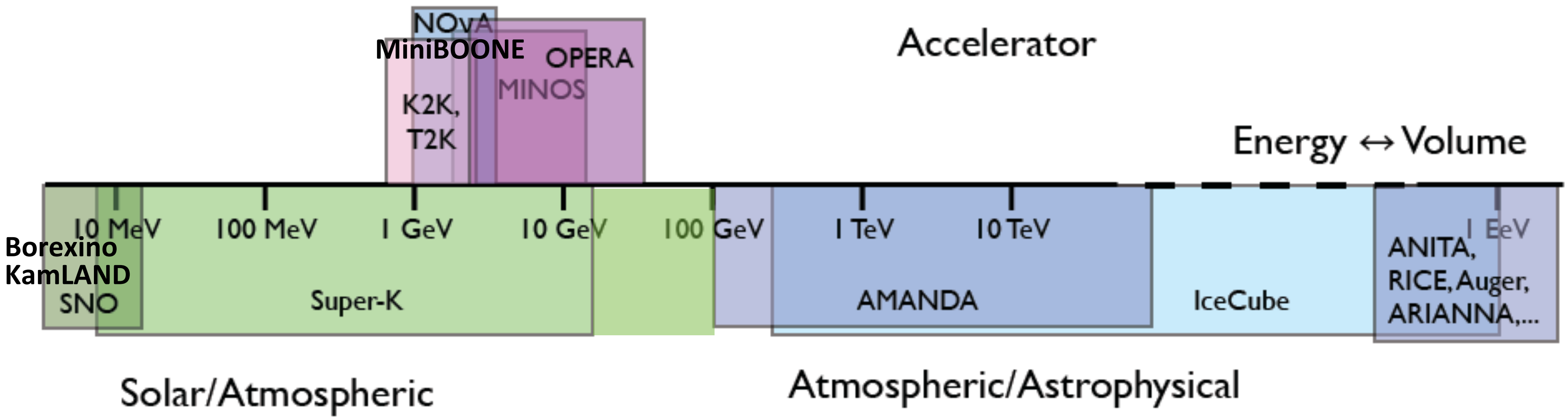
Snowmass on the Mississippi, July 31, 2012

This is not a comprehensive summary. Highlights of opportunities!

Neutrino sources provide many opportunities

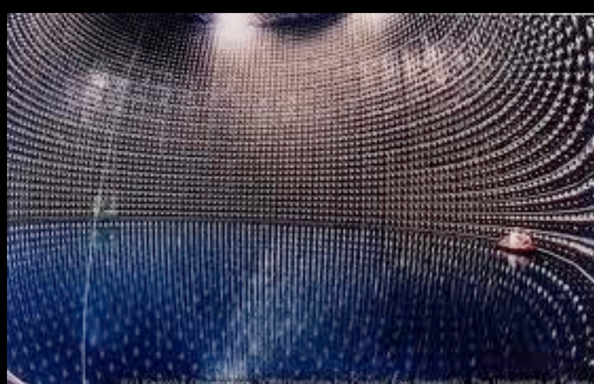


Tools of Discovery - Neutrino Detectors

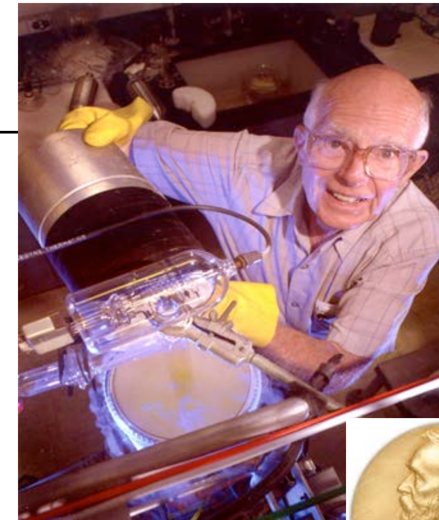


detectors must match requirements of ν sources, leads to
a broad field with a variety of detectors and techniques

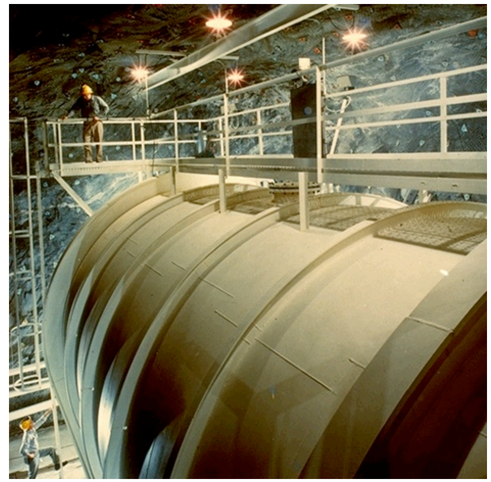
Non-accelerator based



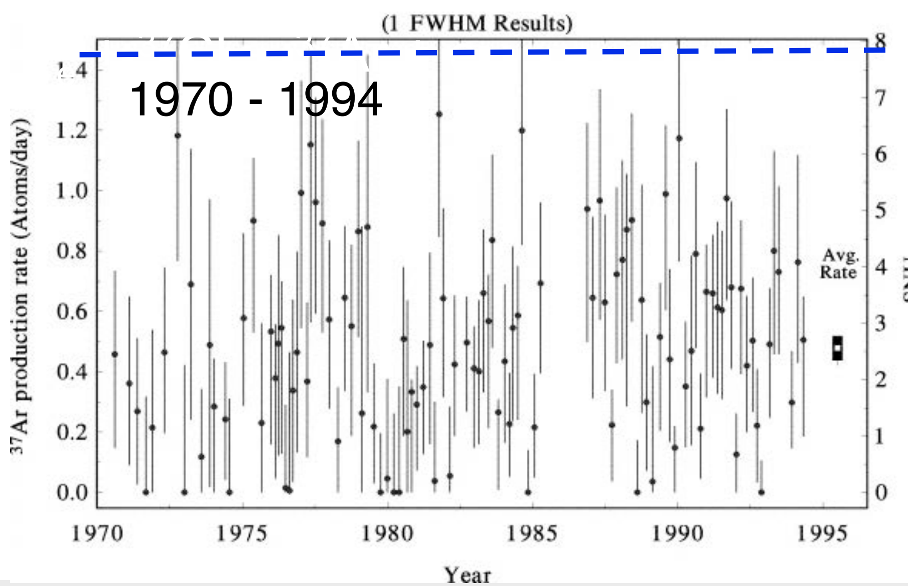
The First Anomaly



Cl-Ar Solar Neutrino Experiment at Homestake



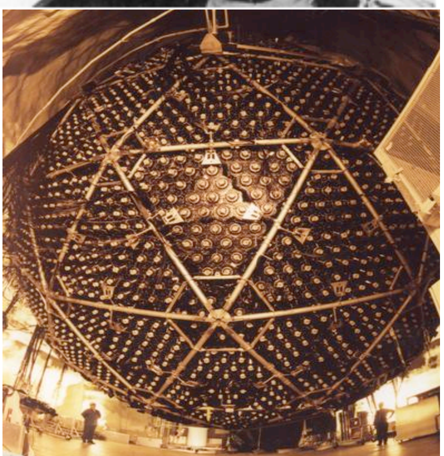
"deficit" of solar neutrinos

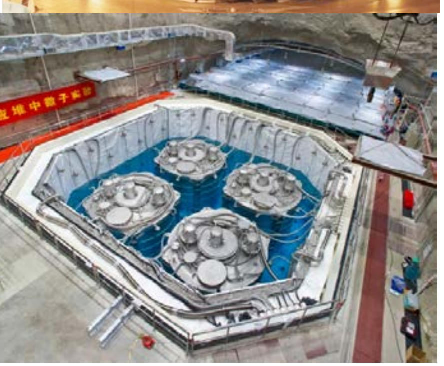


standard solar model

experiment only sensitive to ν_e

Discoveries of Neutrino Oscillation





1968 Ray Davis detects 1/3 of expected solar neutrinos.
(Nobel prize in 2002)

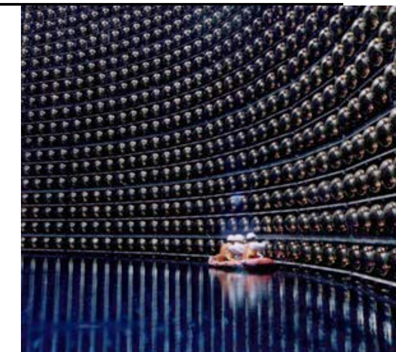
1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

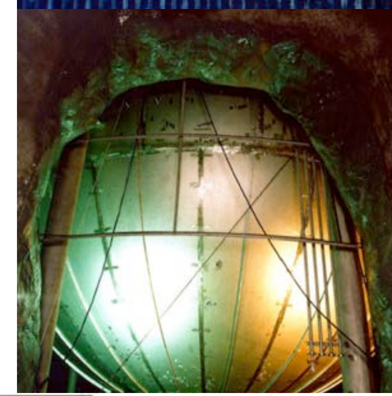
2001/2002 SNO finds evidence for solar ν_e flavor change.

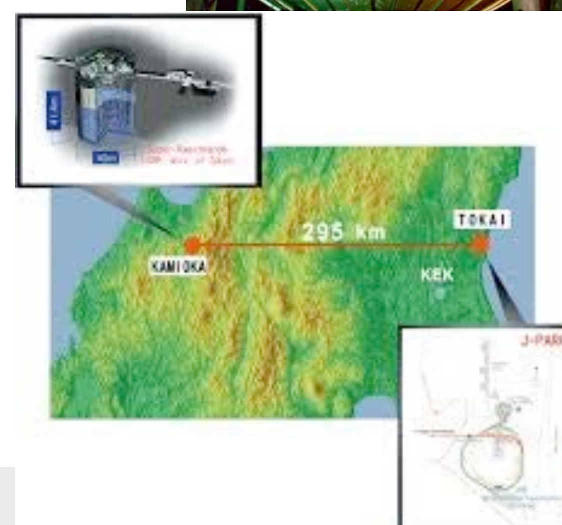
2003 KamLAND discovers disappearance of reactor $\bar{\nu}_e$

2012 Daya Bay, Double Chooz, RENO measure θ_{13}

2013 T2K sees ν_e appearance





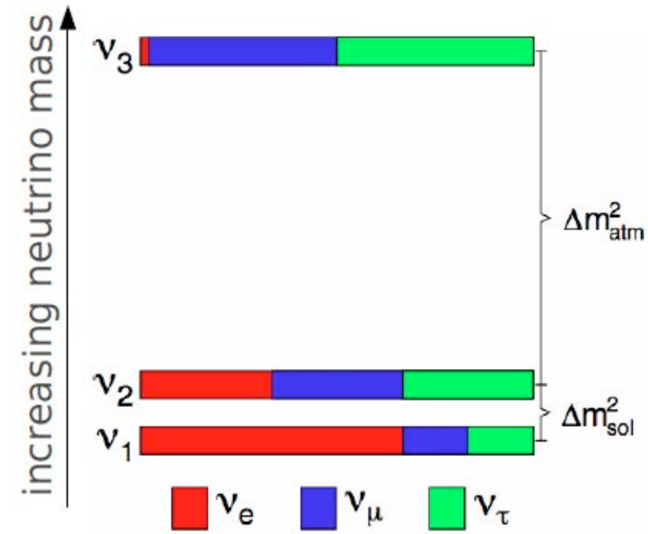


Neutrino Oscillation Implies Neutrino Mass

mass eigenstates ≠ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate



Observables in oscillation experiments

energy E and baseline L

oscillation frequency Δm^2

oscillation amplitude θ

$$P_{i\to j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Parameterized in a mixing matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

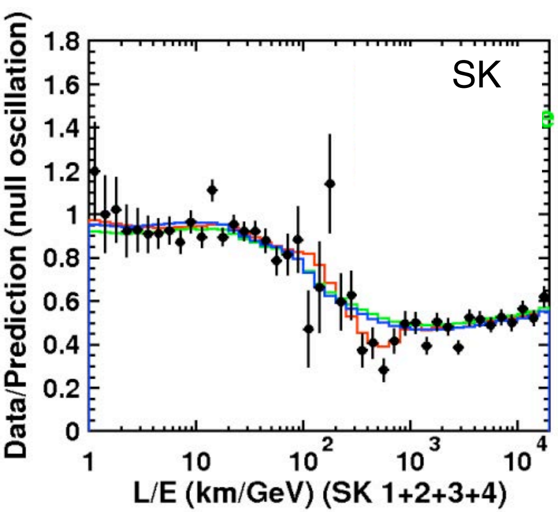
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

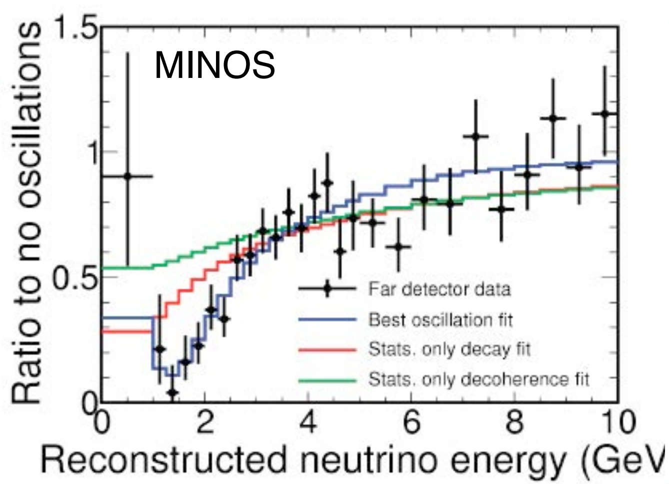
Neutrino Oscillation Measurements

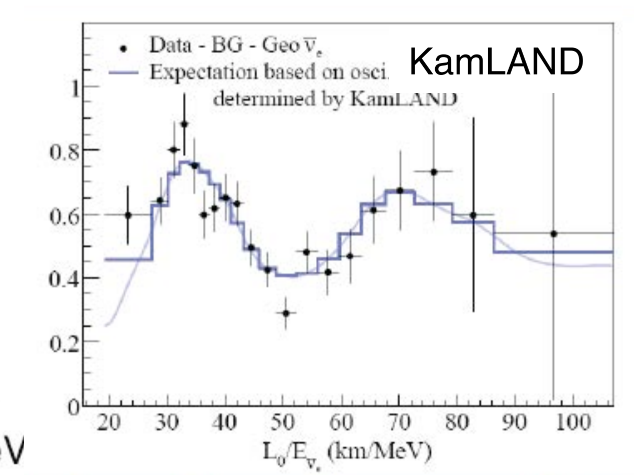
Lots of Experimental Data

- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely to ν_τ (SK, MINOS)
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear at L~250, 700 km (K2K, T2K, MINOS)
- accelerator ν_μ appear as ν_e at L~250, 700 km (T2K, MINOS)
- solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)

Experiments have demonstrated oscillation L/E pattern







matter effects can be probed in long-baseline experiments or extreme environments

Neutrino Mixing is Different

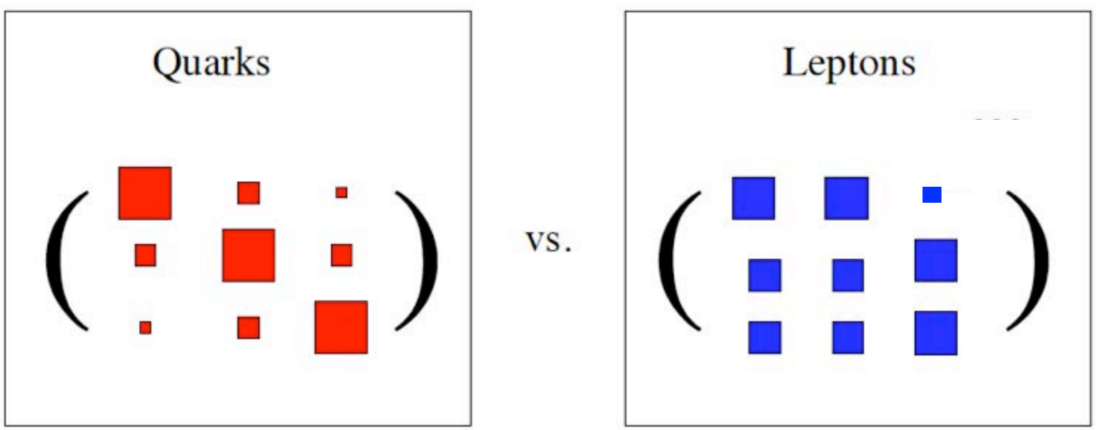
Mixing Angles

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, reactor}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$



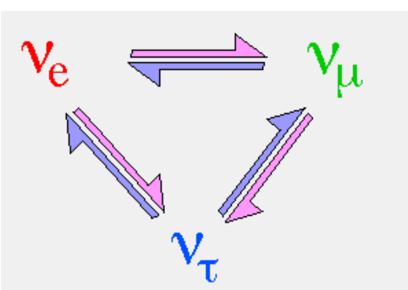
Neutrino Oscillation Measurements

Experiments provide complementary data

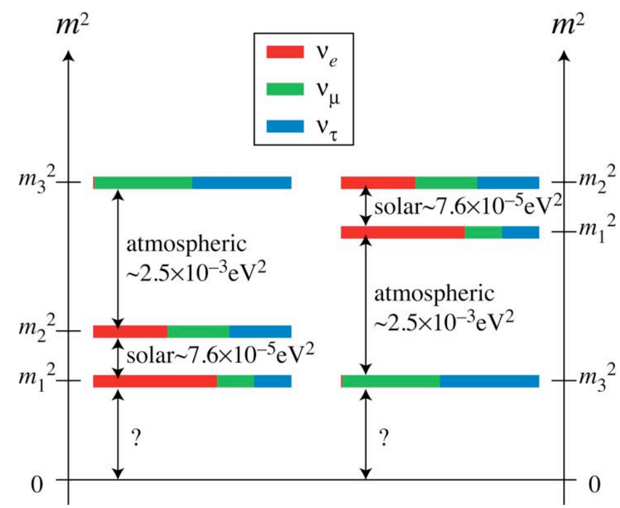
	Dominant	Important
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\rm cp}$	θ_{13} , θ_{23}

Gonzalez-Garcia et al, ICHEP2012

Complete suite of measurements can over-constrain the 3-ν framework

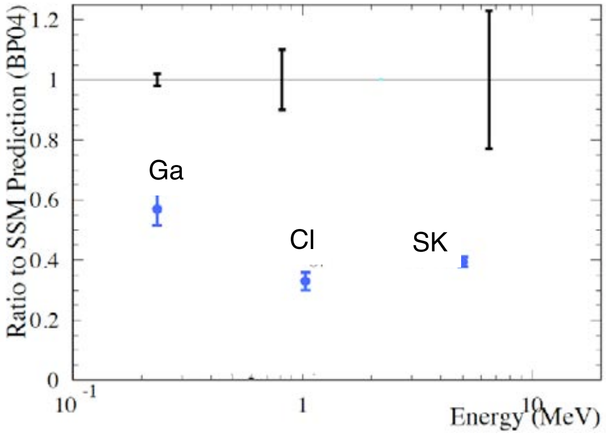


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

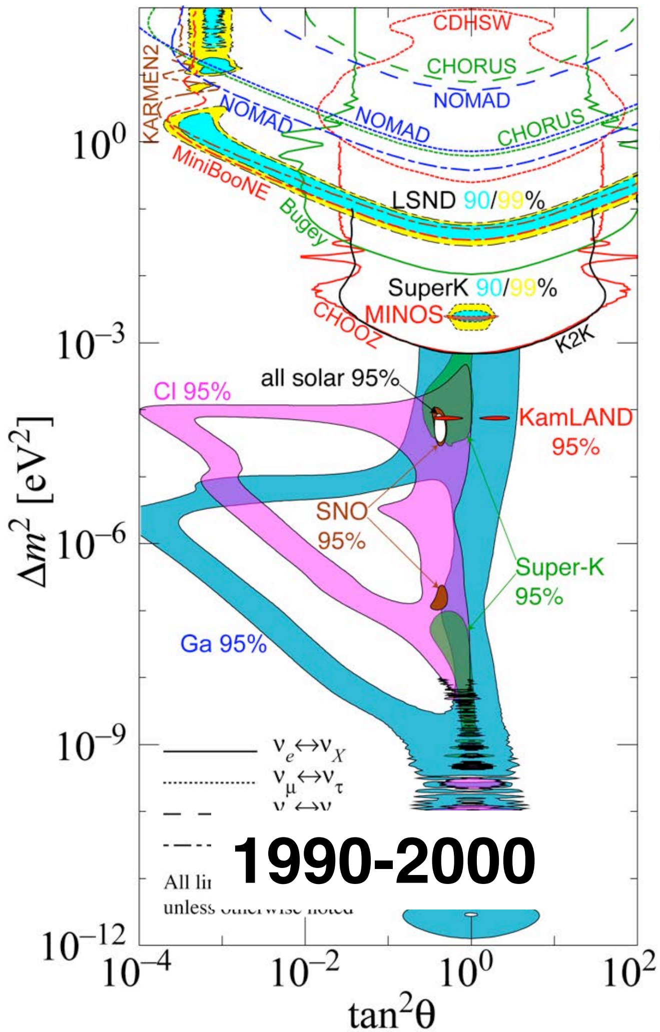


From Anomalies to Precision Oscillation Physics

solar neutrino problem | **oscillation searches** | **precision measurements**

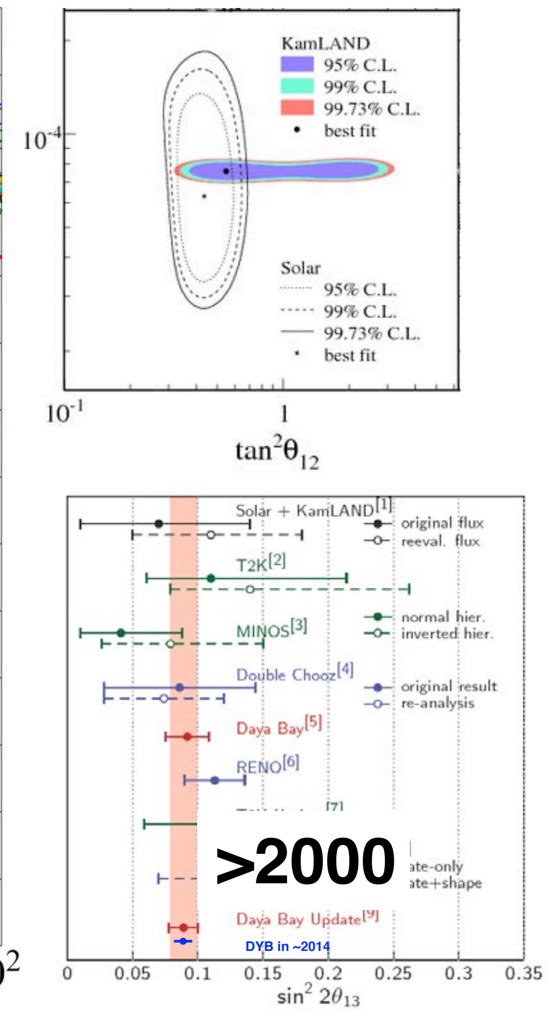


1960-1990



1990-2000

http://hitoshi.berkeley.edu/neutrino

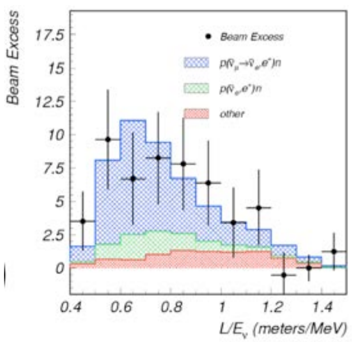


>2000

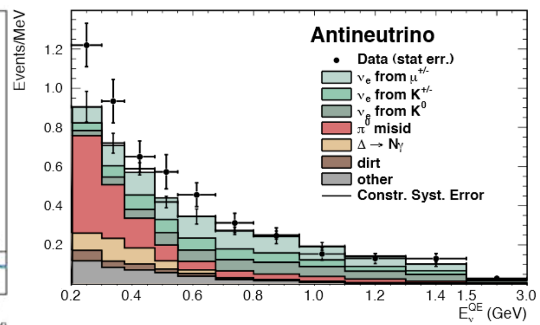
Recent Anomalies

Anomalies in 3-ν interpretation of global oscillation data

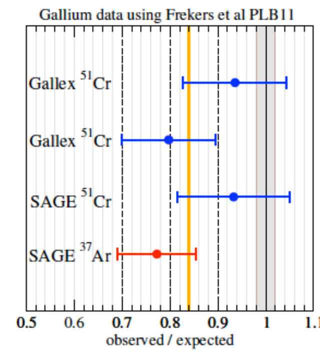
LSND



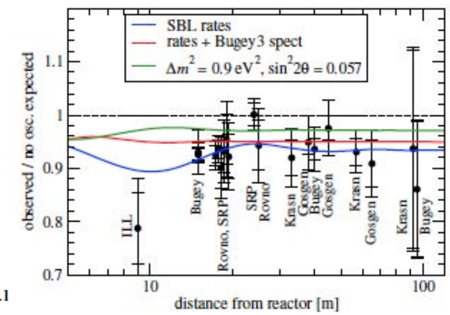
MiniBoone



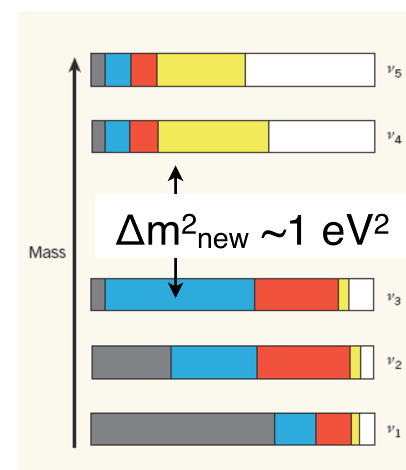
Ga Source



Reactor



LSND ($\bar{\nu}_e$ appearance)
MiniBoone ($\bar{\nu}_e$, ν_e appearance)
Ga anomaly (ν_e appearance)
Reactor anomaly ($\bar{\nu}_e$ disappearance)



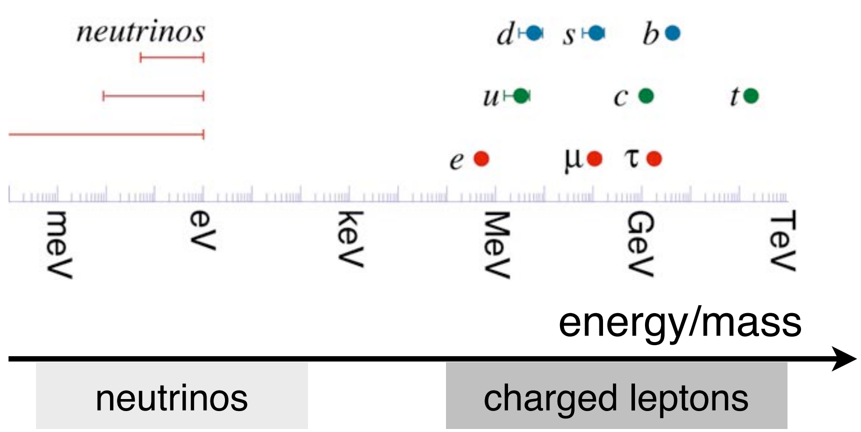
new oscillation signal requires $\Delta m^2 \sim O(1\text{eV}^2)$ and $\sin^2 2\theta > 10^{-3}$

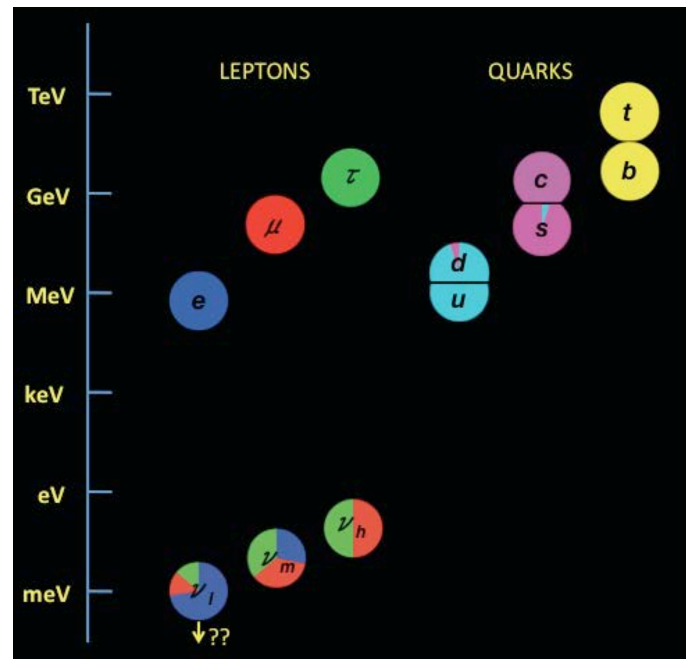
New physics or experimental artifacts?

Planning experiments with reactors, radioactive sources, and accelerators to confirm/refute short-baseline anomalies

Neutrinos - Open Questions

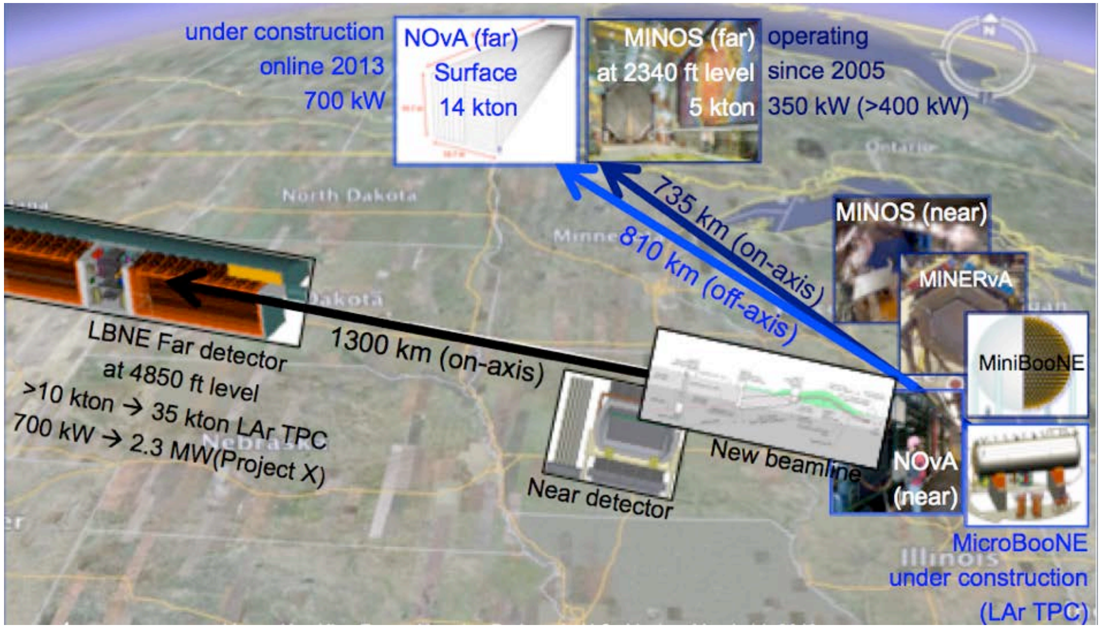
- Neutrino have mass, but why are they so light?
- What is the absolute mass scale?
- Do neutrinos have Majorana mass?
- Normal or inverted mass ordering?
- Is θ_{23} maximal?
- CP violation?
- Are there more than 3ν?





Precision Oscillation Measurements

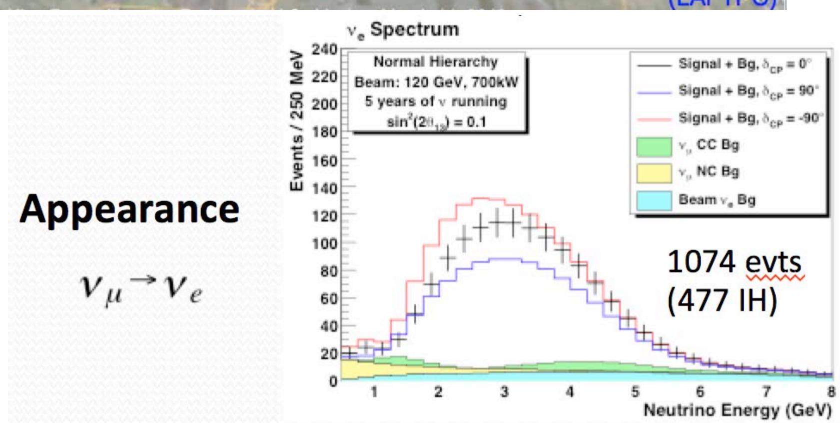
Studying neutrino flavor change as a function of distance and energy

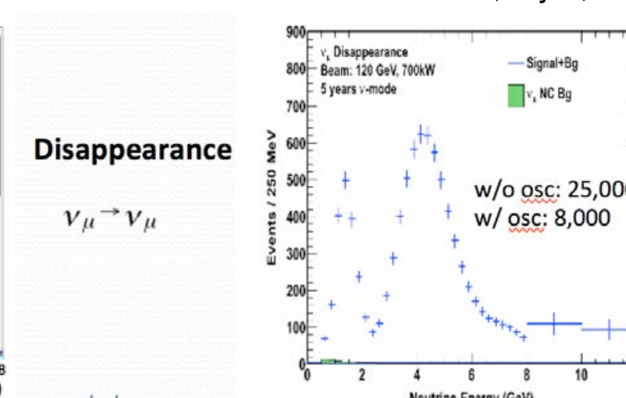


accelerator-based program over short and long baselines

LBNE 34kt, 5 yrs, ν

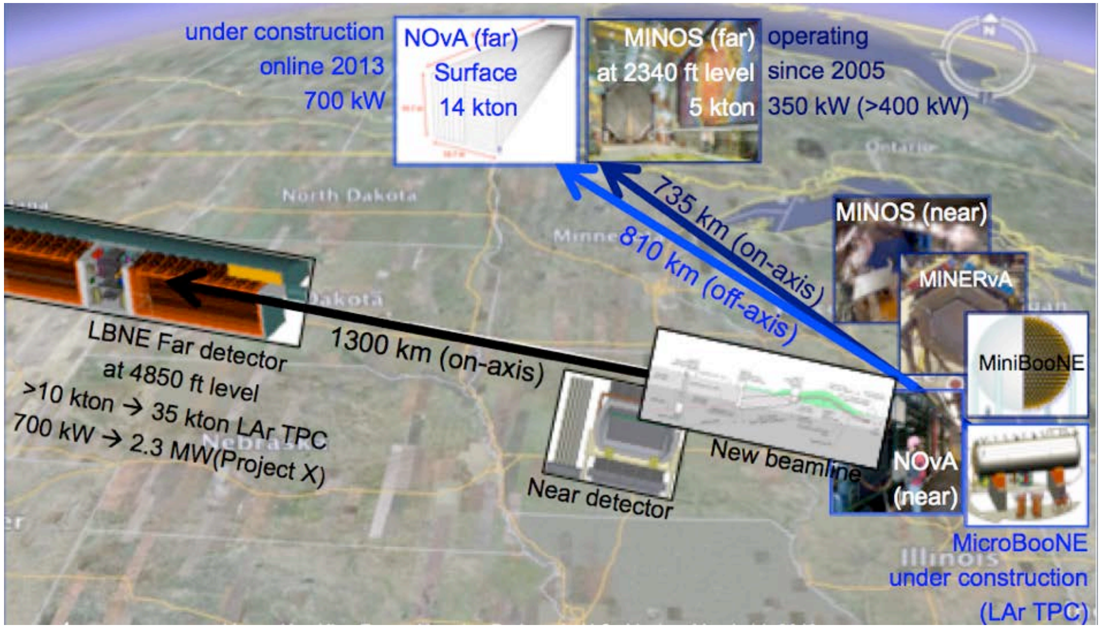
measuring appearance and disappearance





Precision Oscillation Measurements

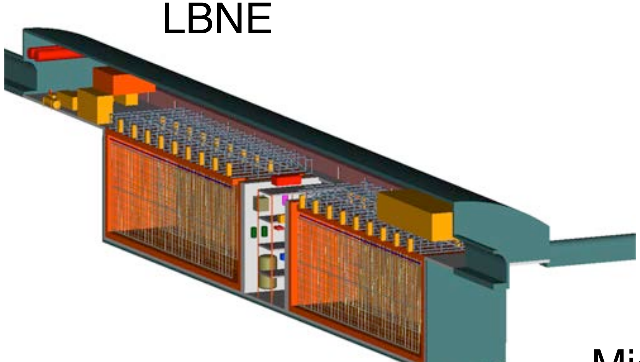
A staged program of experiments for the next decade

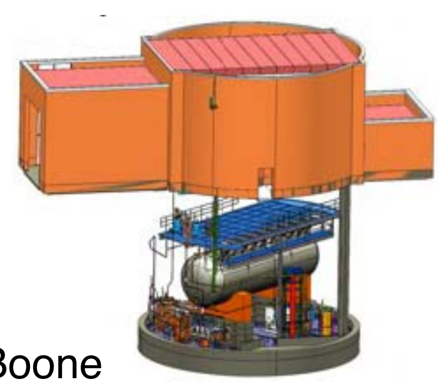


NOvA

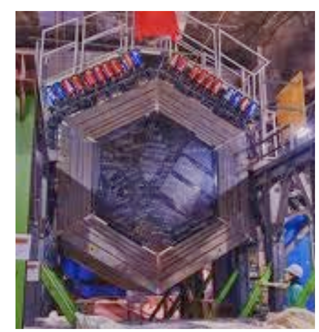
MINOS+

LBNE





MicroBoone

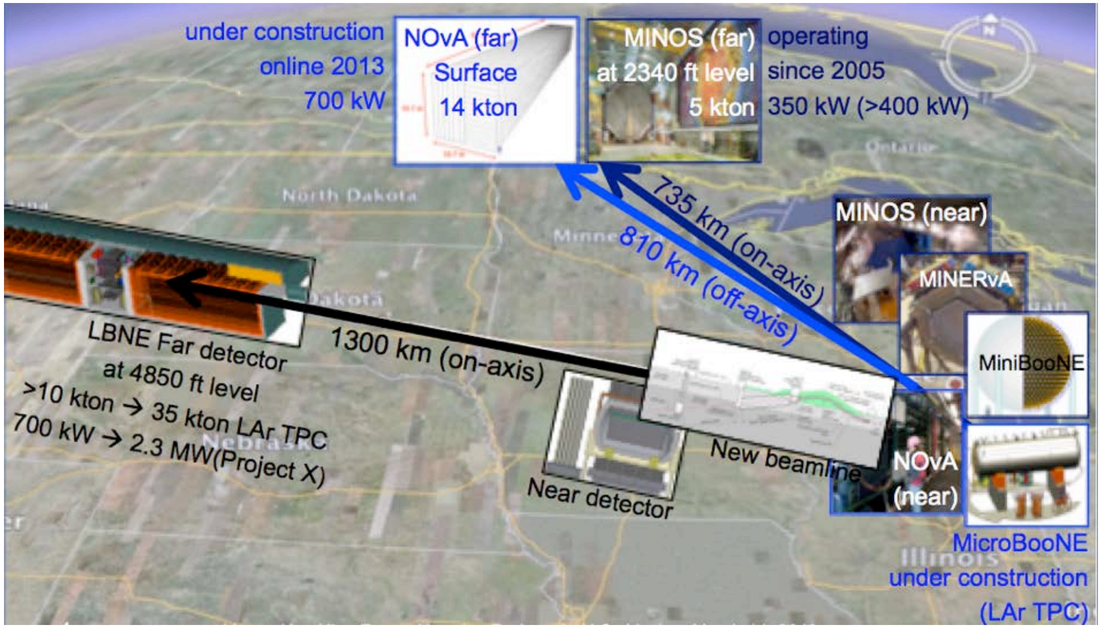


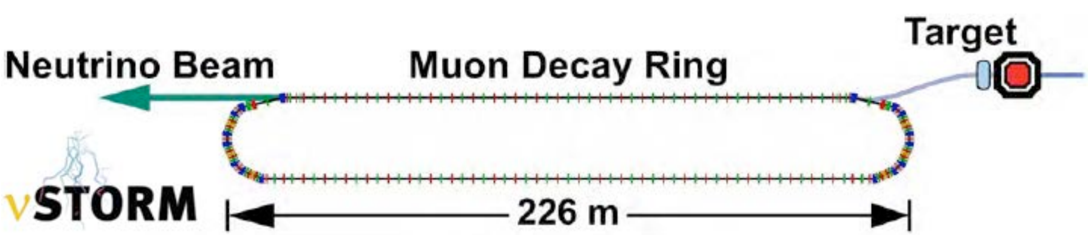
Minerva

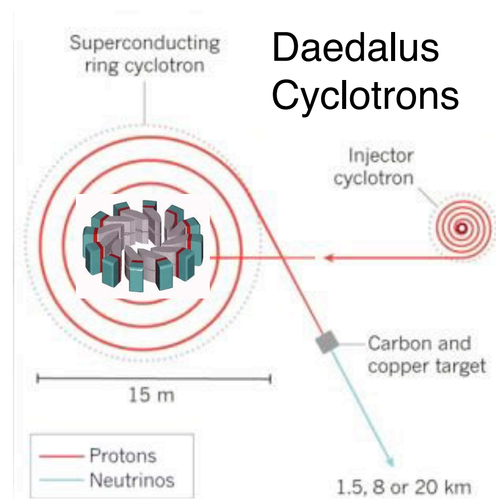
detectors at various scales

Precision Oscillation Measurements

A phased development of accelerator capabilities

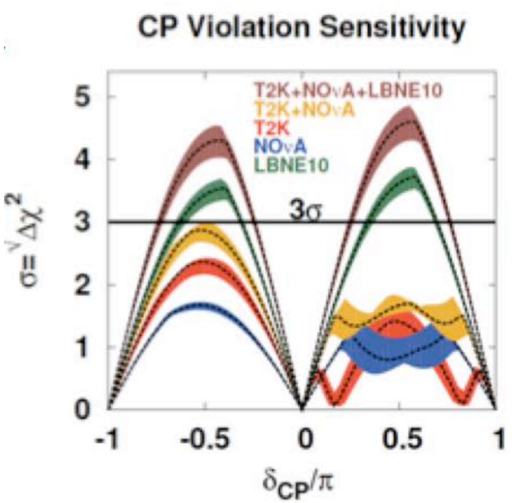


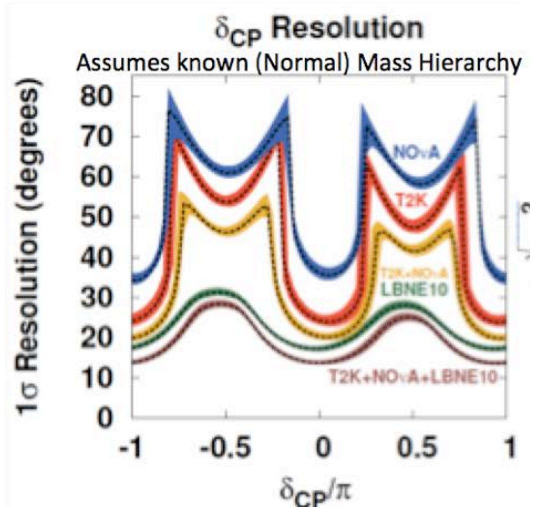


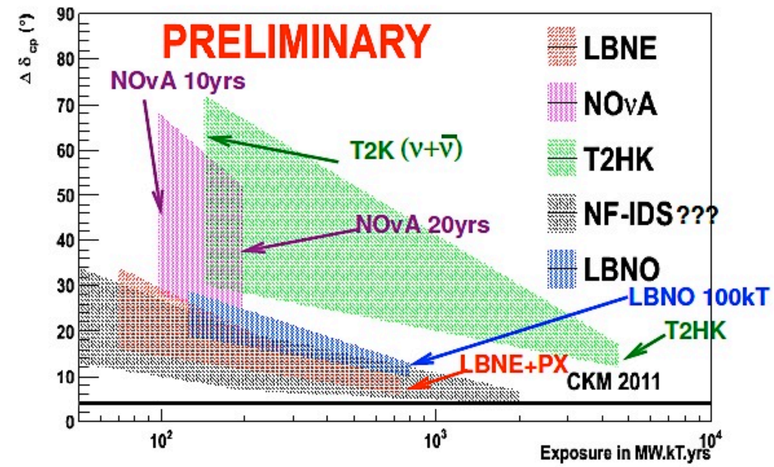


Precision Oscillation Measurements

Searching for CP violation

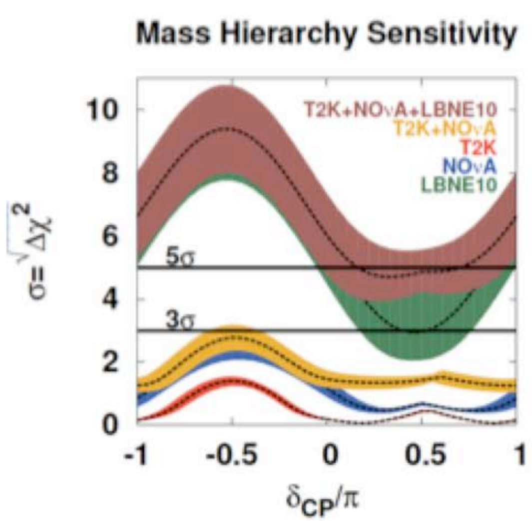




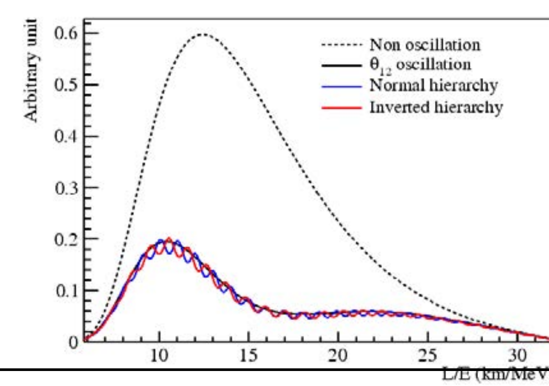


exposure of order of Mt.MW.yr, very long baseline (> 1000 km) and tight control of systematics (< 2% on signal) is needed to reach CKM level precision

Determining the mass hierarchy

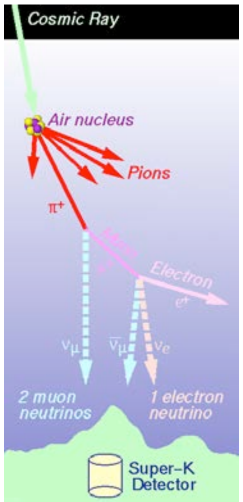


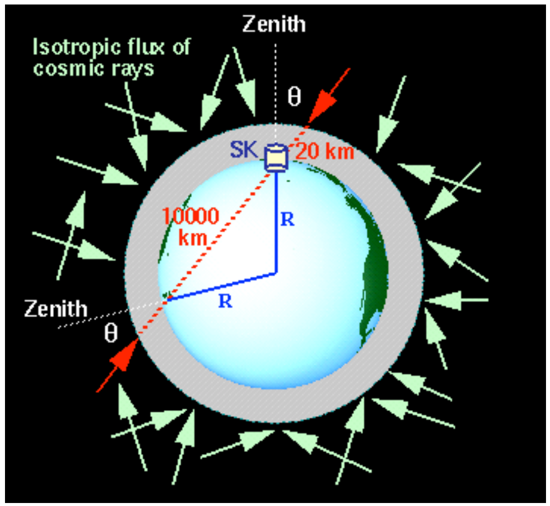
alternative approaches to mass hierarchy:
reactor experiments at ~50km baseline;
atmospheric neutrinos



Oscillation Physics with Atmospheric Neutrinos

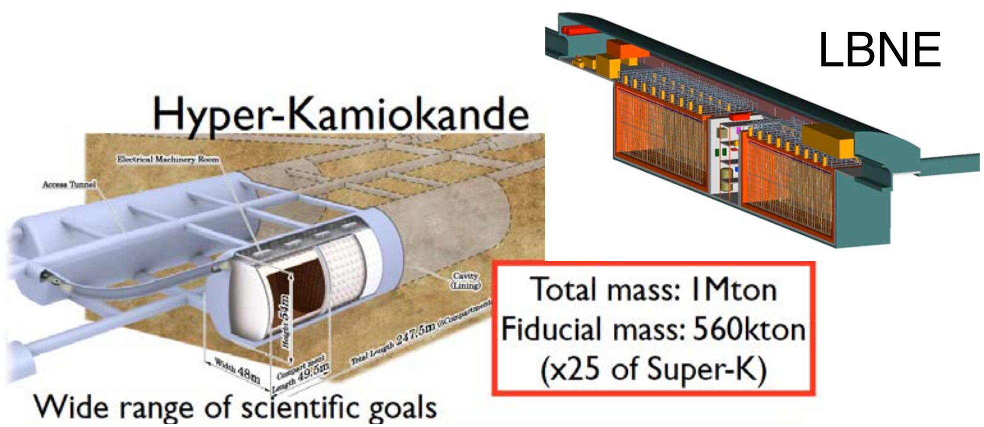
Atmospheric neutrinos observable in a large underground detectors are sensitive to all currently unknown oscillation parameters





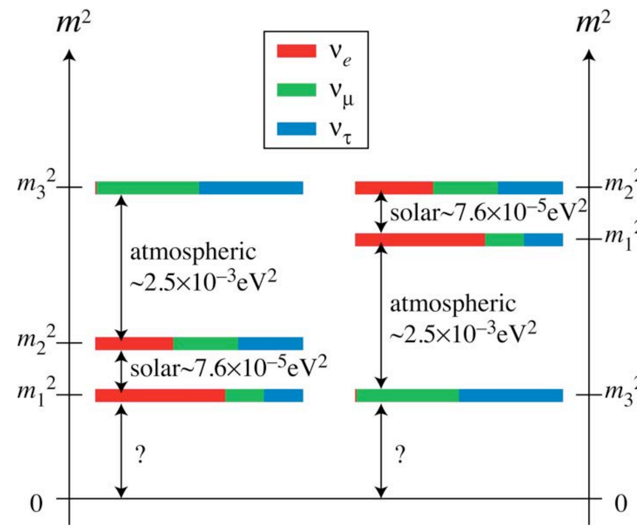
large underground detectors enable other physics, e.g. proton decay searches

multi-purpose detectors when placed in beam

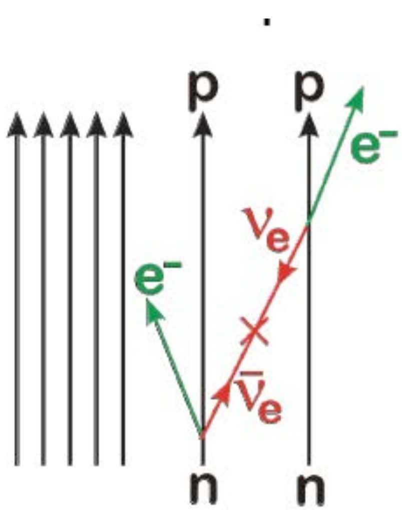


Importance of Mass Hierarchy

What is the flavor content of the lightest neutrino mass state?

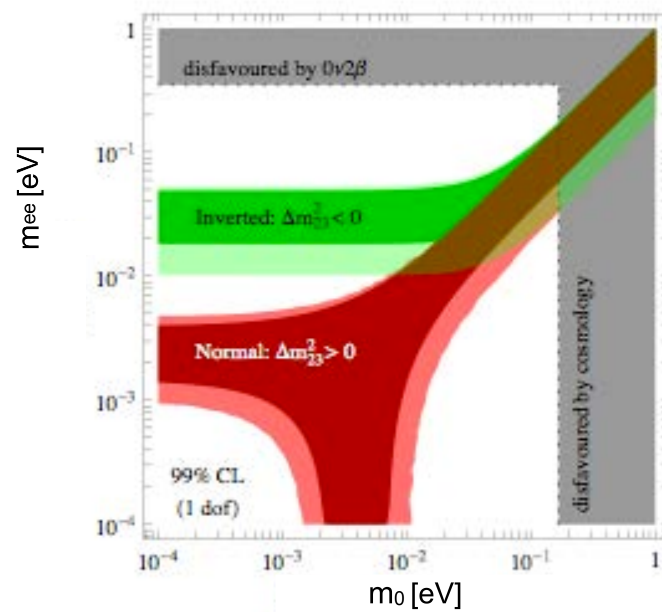


Knowing the mass hierarchy will help us understand the nature of neutrino mass from neutrinoless double beta-decay (0νββ).



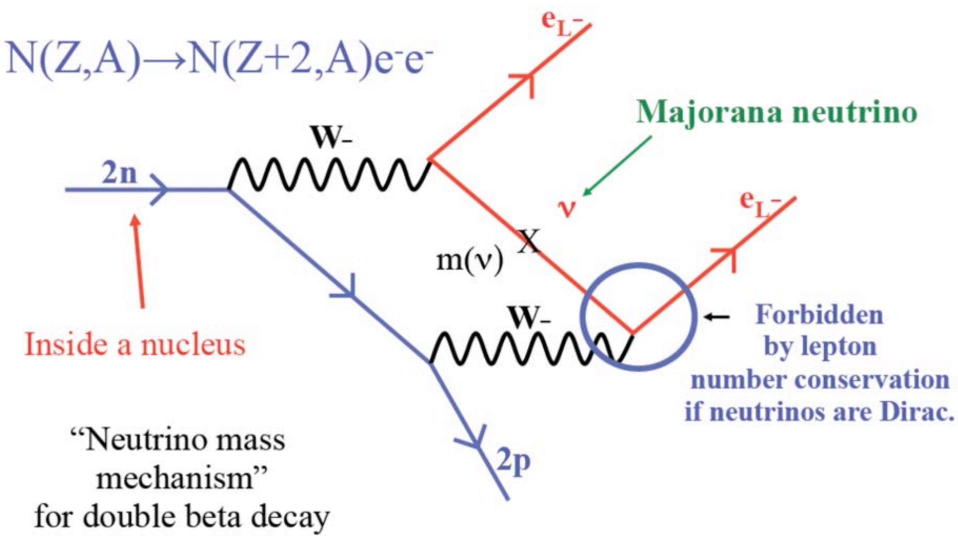
$$\Gamma_{0\nu} = G_{0\nu} \mid M_{0\nu} \mid^2 \left\langle m_{\beta\beta} \right\rangle^2$$

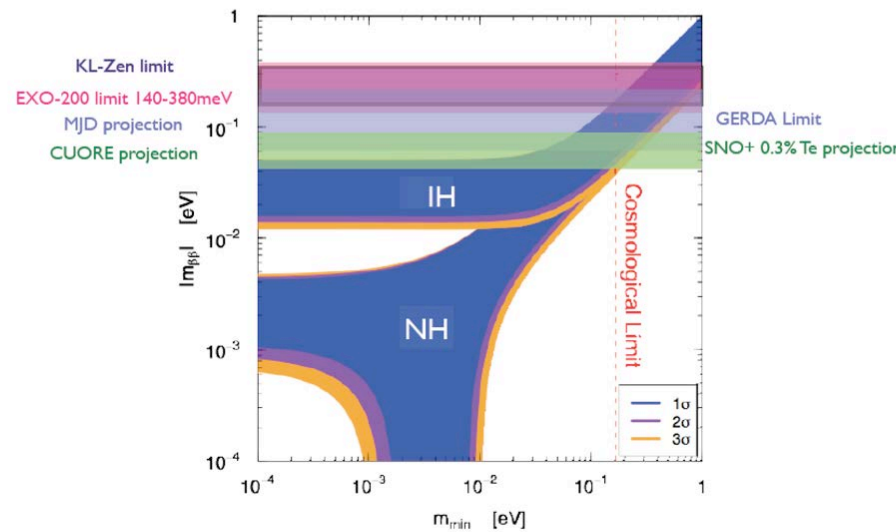
0νββ depends on effective neutrino mass



Majorana or Dirac Neutrino Masses?

Neutrinoless double beta decay is the only feasible experimental approach to establish Majorana mass of neutrinos





observation of $0\nu\beta\beta$ would imply

- lepton number non-conservation
- Majorana nature of neutrinos

$0\nu\beta\beta$ allow us to determine

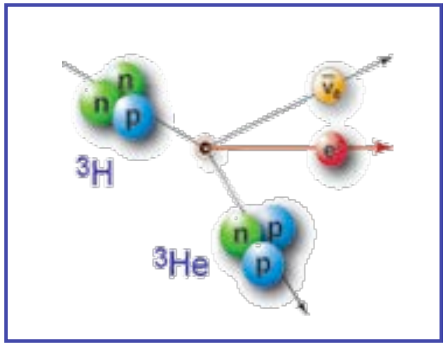
- effective neutrino mass

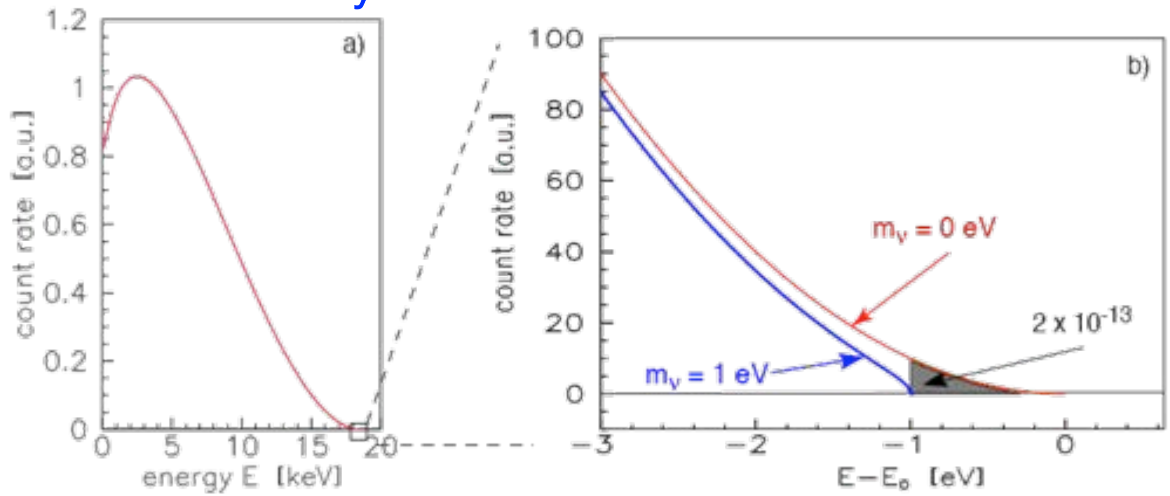
Several technologies feasible. Ready to explore the inverted hierarchy region.

Majorana neutrino mass = beyond SM physics

Absolute Neutrino Mass

Precision measurements of beta decay to determine absolute neutrino mass





$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

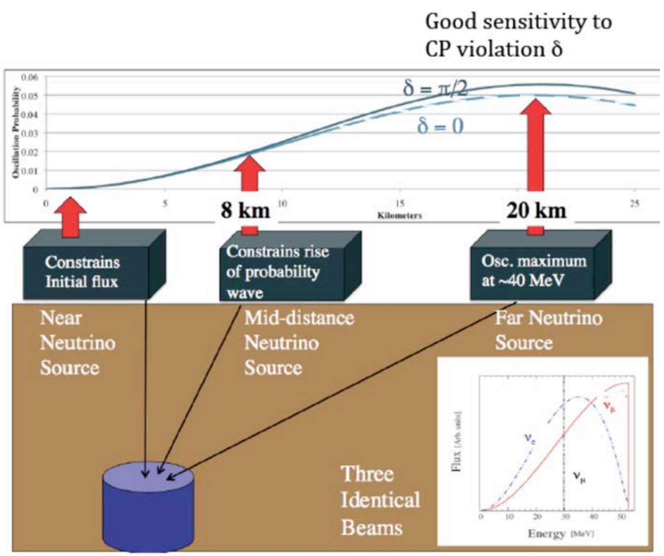
For $m_1 \gtrsim 100$ meV and no sterile neutrinos, the beta spectrum simplifies to an “effective mass”

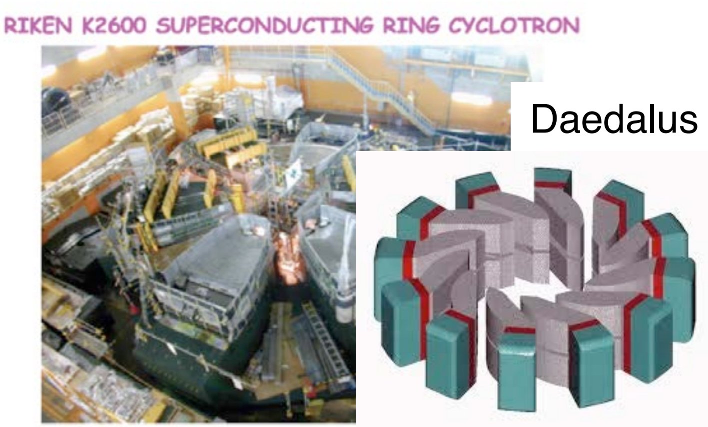
$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}}$$

Smallness of neutrino mass may be related to GUT- or Planck-scale physics.

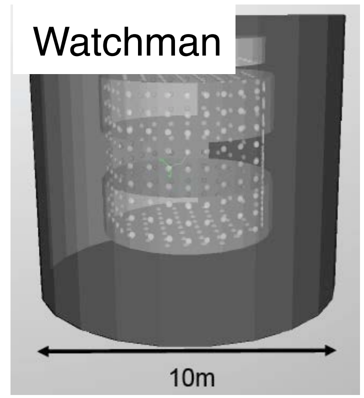
Synergies and Applications - Examples

Cyclotrons for neutrino physics
(and industrial applications)





Neutrino detectors for reactor monitoring and non-proliferation



remote discovery of undeclared nuclear reactors with large detectors at km scale

US Short-Baseline Experiment

reactor antineutrino studies at short baselines

Summary

- Recent discoveries have shown that neutrinos mix and have mass. Evidence for new physics.
- A staged program of neutrino oscillation experiments is underway to make precision measurements of oscillation parameters, test 3-flavor paradigm, and understand neutrino interactions.
- Historic anomalies have turned into discoveries of solar and atmospheric neutrino oscillations. Neutrinos may continue to surprise us!
- The nature of neutrino mass is not yet understood and may hold the clue to physics beyond the Standard Model.
- Synergies with instrumentation and technology developments; connections with other frontiers.

This is not a comprehensive summary. Apologies for any omissions.
Thanks to many colleagues for input, figures, and comments.